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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods

Otávio Cavalett · Mateus Ferreira Chagas · Joaquim E. A. Seabra · Antonio Bonomi

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Abstract
Purpose The main objective of this study is to expand the discussion about how, and to what extent, the environmental performance is affected by the use of different life cycle impact assessment (LCIA) illustrated by the case study of the comparison between environmental impacts of gasoline and ethanol form sugarcane in Brazil.
Methods The following LCIA methods have been considered in the evaluation: CML 2001, Impact 2002+, EDIP 2003, Eco-indicator 99, TRACI 2, ReCiPe, and Ecological Scarcity 2006. Energy allocation was used to split the environmental burdens between ethanol and surplus electricity generated at the sugarcane mill. The phases of feedstock and (bio)fuel production, distribution, and use are included in system boundaries.
Results and discussion At the midpoint level, comparison of different LCIA methods showed that ethanol presents lower impacts than gasoline in important categories such as global warming, fossil depletion, and ozone layer depletion. However, ethanol presents higher impacts in acidification, eutrophication, photochemical oxidation, and agricultural land use categories. Regarding to single-score indicators, ethanol presented better performance than gasoline using ReCiPe Endpoint LCIA method. Using IMPACT 2002+, Eco-indicator 99, and Ecological Scarcity 2006, higher scores are verified for ethanol, mainly due to the impacts related to particulate emissions and land use impacts.
Conclusions Although there is a relative agreement on the results regarding equivalent environmental impact categories using different LCIA methods at midpoint level, when single-score indicators are considered, use of different LCIA methods lead to different conclusions. Single-score results also limit the interpretability at endpoint level, as a consequence of small contributions of relevant environmental impact categories weighted in a single-score indicator.

Keywords Biorefinery · Categories of impact · Environmental impacts · Life cycle impact assessment (LCIA) · Midpoint modeling · Single score · Sugarcane

1 Introduction

Replacement of fossil fuels by biofuels has been considered an important alternative in the transition process to a low carbon economy in several countries. It has been recognized that large-scale production and use of ethanol from sugarcane present some environmental and energy security benefits in comparison to gasoline as liquid fuel for transportation (Macedo et al. 2008; Cherubini and Ulgiati 2010; González-García et al. 2010; Halleux et al. 2008; Macedo 2005; Ometto et al. 2009; Renouf et al. 2010; 2011; Seabra et al. 2010, 2011; Seabra 2008; Walter et al. 2011). The life cycle assessment (LCA) has been broadly used to evaluate the comparative environmental impacts of different transportation fuel and biofuels options. However, in previous LCA studies of bioenergy production systems, methodological differences could be observed among which the choice

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O. Cavalett (✉) · M. F. Chagas · J. E. A. Seabra · A. Bonomi
Laboratório Nacional de Ciência e Tecnologia do Bioetanol,
CTBE, Caixa Postal 6170,
13083-970, Campinas, Brazil
e-mail: otavio.cavalett@bioetanol.org.br

J. E. A. Seabra
Faculdade de Engenharia Mecânica,
Universidade Estadual de Campinas,
Rua Mendeleyev 200,
13083-860, Campinas, Brazil

of the life cycle impact assessment (LCIA) methods used. For example, CML was used by Luo et al. (2009), Bai et al. (2010), Botha and von Blottnitz (2006), Cherubini and Ulgiati (2010), González-García et al. (2010); EDIP by Ometto et al. (2009), impact 2002+ by Renouf et al. (2010, 2011), and Eco-Indicator99 by Uihlein and Schebek (2009) and Halleux et al. (2008).

With its translation of the product system's environmental flows from the life cycle inventory phase (LCI) into scores that represent their impacts on environment, LCIA is essential for the interpretation of the results in relation to the questions posed in the LCA goal definition (Finnveden et al. 2009). The challenge of LCIA is to evaluate the potential impact of the emitted substances by using a procedure that is ideally simple, applicable consistently to all substances, using a common unit of measurement, and giving results that are comparable between impact categories. Over the years, researchers have worked to overcome these challenges and today various LCIA methods are integrated in the most commonly used LCA software (Dreyer et al. 2003; Pizzol et al. 2011a). However, when dealing with the assessment of environmental impacts of the various substances, two problems arise: different LCIA methods provide very different results, and consequently, uncertainties in such results are high (Pizzol et al. 2011a; Renou et al. 2008).

Since the early 1990s, many attempts have been made to harmonize LCIA approaches. The ISO 14041 (1998) standard on impact assessment published in 1999, now part of ISO 14044 (2006), brought some standardization on basic principles. However, this still allows for many different LCIA methods to be ISO compatible (JRC 2010). There are some examples in LCIA literature of best approaches, the underlying principles, and in some cases the models but they have not resulted in a uniform, globally accepted set of LCIA methods (Udo de Haes et al. 2002; JRC 2010; Finnveden et al. 2009). Furthermore, according to Zhou et al. (2011), there is no clear information or even guidelines for the general users to choose proper LCIA methods. Renou et al. (2008) point out that the chosen method is rarely discussed and when several methods are used no comparison is made between the results. It is legitimate to ask whether the choice of one of the existing LCIA methods, which are all scientifically sound, could influence LCA results. This is a key issue when the results of an assessment should be presented to stakeholders who are not LCA specialists. Dreyer et al. (2003) adds that the LCA practitioner will not find one obvious choice among the LCIA methods, and the question therefore naturally arises: "Does it make any difference to my conclusions which method I choose?" It is possible to find in literature previous studies comparing different LCIA methodologies, taking in consideration one or more of the impact categories and also the different methodological stages (characterization, normalization, and weighting; Zhou et al. 2011; Pizzol et al. 2011a, b; Caneghem et al. 2010; Pant et al. 2004; Renou et al. 2008; Dreyer et al. 2003). Studies from Pizzol et al. (2011a, b) concluded that using different LCIA methodologies showed no agreement between the methods regarding the assessment of the impact of metals on human health and ecotoxicological impact on the aquatic and terrestrial ecosystem. Zhou et al. (2011) used a case study to provide a useful framework for selection of LCIA methods; however, this study considered only two LCIA methods. Caneghem et al. (2010) evaluated the impact on human health of industrial emissions to air and concluded that the choice of the LCIA methods can highly influence the conclusions. Pant et al. (2004) compared three different LCIA methods for aquatic ecotoxicity impacts. Dreyer et al. (2003) compared three LCIA methods and concluded that it does matter which LCIA method is chosen. On the other hand, Renou et al. (2008) used five LCIA methods to evaluate five impact categories related to a wastewater plant operation and concluded that the choice of one or the other LCIA methods is not a critical issue as the results they provide are similar.

Therefore, a comprehensive study considering all the environmental impact categories of several midpoint and endpoint LCIA methods applied to the bioenergy sector is extremely important to improve the understanding about different LCIA methods. In face of that, the main objective of this study is to expand the discussion about how, and to what extent, the environmental performance is affected by the use of different LCIA illustrated by the case study of the comparison between gasoline and ethanol from sugarcane in Brazil

In this paper, seven different LCIA methods have been used for the comparative assessment. The CML 2001 (Guinée 2001) LCIA method aims to offer best practice for midpoint indicators, operationalising the ISO14040 series of standards. It includes recommended methods for normalization but weighting is not included. Eco-indicator 99 (Goedkoop and Spriensma 2001) was developed with the objective of simplify interpretation and weighting of results. One of the potential applications is the calculation of single-point eco-indicator scores that can be used for decision making. The EDIP 2003 (Hauschild and Potting 2005) supports the classic emission-related impact categories at a midpoint level as well as resources. It includes normalization and weighting of environmental impacts based on political environmental targets. The Impact 2002 LCIA method (Jolliet et al. 2003) proposes a feasible implementation of a combined midpoint/damage approach, linking different types of elementary flows and other interventions with 14 midpoint categories and four damage categories. ReCiPe (Goedkoop et al. 2009) is a follow up of Eco-indicator 99 and CML 2002 methods. It integrates midpoint

and endpoint approach in a consistent framework and almost all impact categories were updated. Ecological Scarcity (Frischknecht et al. 2009) method allows a comparative weighting and aggregation of various environmental interventions by use of so-called ecofactors. These ecofactors are based on the annual actual flows and on the annual flow considered as critical in a defined area. The method is built on the assumption that a well established environmental policy framework may be used as reference framework for the optimization and improvement of individual products and processes. TRACI 2 (Jane et al. 2002) was developed by the Environmental Protection Agency (EPA) as a midpoint method that represents the environmental conditions in the USA.

2 Material and methods

2.1 Data collection

This study provides an updated and comprehensive life cycle inventory for sugarcane ethanol in Brazil considering the stages of agricultural production, transport, ethanol production, and its final use. Both sugarcane agricultural data and computer simulation of industrial process were validated based on literature, experts information, and field work. Other background data for production of inputs used for sugarcane and ethanol production were sourced from Ecoinvent Database (Swiss Centre for Life Cycle Inventories 2009). However, some of the inputs contributing to higher environmental impacts were adapted to the Brazilian production scenario (e.g., fertilizers and sulfuric acid). The life cycle inventory for ethanol production and use was used for comparing results from different LCIA methods.

The sugarcane-growing stage represents an average production scenario in the center–south region of Brazil. This region was chosen because it is responsible for more than 90 % of the total sugarcane and ethanol production in Brazil (UNICA 2011). It was also considered a scenario where sugarcane is totally harvested mechanically, without the previous burning of trash (sugarcane tops and leaves). This assumption in based on the governmental mandate that determines a gradual phase out of pre harvesting burning in São Paulo till 2021 and the Environmental Protocol that anticipated this deadline for 2014 (in areas where mechanization is possible). The quantities of the main inputs and outputs for the sugarcane growing, harvesting and transport to the mill stages are shown in Electronic supplementary material (ESM Table S1).

The industrial data were obtained based on computer simulation of ethanol production process, and also from literature and from industries representing a modern technological scenario (marginal data) for sugarcane-processing facilities (including unit operations typical of those found in the new Brazilian bioethanol industries). In the considered sugarcane processing scenario, 500 metric tons of sugarcane are processed per hour. The main products are hydrous ethanol (93.0 wt% ethanol) and electricity. It was also considered modern efficient cogeneration systems, employing 90 bar boilers and condensing extraction steam turbine for production of steam and electric energy, allowing the generation of a considerable amount of surplus electricity to be sold to the grid. The quantities of inputs and outputs for the industrial ethanol production stage are shown in ESM (Table S2).

The gasoline used in Brazil normally is a blend of 75 % gasoline and 25 % anhydrous ethanol, in volume (E25). However, the fraction of anhydrous ethanol mixed in the gasoline can vary from 18 to 25 % depending on the governmental policies and ethanol supply capacity. The gasoline E25 inventory was modeled using the process "Petrol, low-sulphur, at regional storage/RER" from Ecoinvent Database (Swiss Centre for Life Cycle Inventories 2009) and anhydrous ethanol. The additional process to the needed for anhydrous ethanol production is the ethanol dehydration process. In this study, it was considered that ethanol dehydration process is carried out at the same factory using molecular sieves. The modifications (in the hydrous ethanol) considered in the life cycle inventory for anhydrous ethanol production were zeolite input (0.026 kg per ton of sugarcane processed) and lower anhydrous ethanol yield (1,923 MJ per ton of sugarcane processed) in comparison to the hydrous ethanol (yield of 1,926 MJ per ton of sugarcane processed, as showed in ESM Table S2).

The average distance considered in this study for the ethanol distribution stage from the sugarcane processing facility to the gas station was 300 km using a lorry with capacity of 16–32 t (Seabra 2008). The emissions of using phase are showed in ESM Table S3. These figures are the emissions per megajoule of fuel used of a flex fuel vehicle running both on ethanol and gasoline E25 in Brazil.

2.2 Functional unit, system boundaries, and allocation

The functional unit used for the comparison between gasoline and ethanol is 1.0E+06 J (1 MJ) of fuel. The stages of (bio)fuel production, distribution, and use are included in system boundaries. According to LCA methodology, allocation is required for multi-output processes. Allocation, defined as the partitioning of input or output flows of a unit process to the product under study, is one of the most crucial issues in the LCA. For the ethanol production system from sugarcane in Brazil, energy allocation based on the energy content (higher heating value) of the process outputs (ethanol and electricity) was applied.

2.3 Midpoint level indicators

At the midpoint level, all the substances listed on LCI are appropriately aggregated into impact categories according a common characteristic in the cause effect chain of the environmental mechanism. These characteristics do not represent the final consequences on environmental pathway of the emissions listed on LCI, but are potential impact indicators. Therefore, it is a recognized as a problem-oriented LCIA method. Some of the commonly related impact categories of midpoint methods are: climate change, ozone layer depletion, human toxicity, ecotoxicity, eutrophication, acidification, resource depletion, and photochemical ozone formation, which show that, at this level, a higher number of impact assessment categories are analyzed compared to the three areas of protection at endpoint level, where the final consequences of the emissions are quantified.

2.4 Endpoint level indicators

The endpoint modeling consists basically of characterizing the severity or consequences of midpoint impacts categories in the areas of protection at endpoint level, which are human health, natural environment, and natural resources. This characterization at the endpoint level requires modeling all the environmental mechanisms that connect the inventory results with their respective impact on the areas of protection. Therefore, it is a damage-oriented LCIA method.

2.5 Selection of LCIA methodologies

Various methods have been developed and are currently available for the assessment of potential environmental impacts in LCA. Table 1 shows the LCIA methods that were considered in this study. These methods have been recently used in the environmental assessment of bioenergy and are available in the database of LCA dedicated software (e.g., SimaPro 7.3 (PRé Consultants)). A description of these methods is summarized by Pizzol et al. (2011b) and detailed additional information on the methods may be accessed from the European Commission, Joint Research Centre webpage on LCA tools, services, and data (http://lca.jrc.ec.europa.eu).

3 Results and discussion

Results for the comparison of the life cycle environmental impacts of ethanol and gasoline are presented and discussed using midpoint and endpoint level indicators calculated using different LCIA methods. However, as pointed out by Renou et al. (2008), the impact categories may be different between methods making comparison not trivial. Even when the impact categories are comparable, the weights associated to the different contributions within a given category are different between methods. It is not straightforward to compare different LCIA methods because the impact categories considered are not the same in the different methods. Even when the approach is comparable, the number of substances considered as well as its classification into impact categories; and also normalization step are normally different. Also, it is important to notice that LCIA results are expressed in different units of measure and are not directly comparable, especially at the characterization level. This happens even between subcategories of the same impact category (e.g., in TRACI the characterization potential is expressed in kilogram benzene equivalents but the non-carc. potential in kilogram toluene equivalents; Pizzol et al. 2011b).

3.1 Comparison using midpoint indicators

Traditional characterization methods are examples of midpoint modeling, meaning that they consider an indicator somewhere between emission and endpoint in the environmental mechanism (a “midpoint”). The indicator is typically chosen where it is judged that further modeling is not feasible or involves too large uncertainties, or where a relative comparison can be made without the need for further modeling (Finnveden et al. 2009). Table 2 presents the environmental impact categories results for ethanol and gasoline using CML, ReCiPe Midpoint, TRACI, EDIP 2003, and Impact 2002+ LCIA methods. Eco-indicator 99 can be also classified as a midpoint LCIA method, but it was not considered in midpoint LCIA methods comparison in this study because the characterizations units for midpoint indicators in this methods are further in the environmental mechanism and, therefore, difficult to be compared with the other methods.

Results of environmental impacts obtained using different midpoint LCIA methods are similar for equivalent categories. Nevertheless, ReCiPe, EDIP 2003, and Impact 2002+ LCIA methods provide more categories for evaluation and comparison than CML and TRACI. In general, comparison of the five selected midpoint LCIA methods shows that ethanol presents better environmental performance than gasoline in important environmental impact categories such as global warming, fossil depletion, and ozone layer depletion. However, there are environmental impacts categories where ethanol presented worse environmental performance than gasoline, such as acidification, eutrophication, photochemical oxidation, and agricultural land use. These categories are, in general, intrinsic to agricultural products and they are expected to be higher than products derived from fossil resources such as gasoline. High values of photochemical oxidation in ethanol impact assessment are mainly associated with local ethanol emissions from distillation. However, these emissions are quite small in the present operational conditions. For eutrophication and acidification, the most

Table 1 Summarized information about the LCIA methods that were considered in this study

Method	Reference	Version of the method used in this assessment (SimaPro)	Midpoint/endpoint	Number of categories considered	Regional validity[a]
CML 2001	Guinée (2001)	CML 2 Baseline 2000, v2.05	Midpoint	10	Global, except for acidification and photo-oxidant formation (Europe)
Impact 2002+	Jolliet et al. (2003)	v2.06	Midpoint/Endpoint	15	Europe for the basic version. For the intake fraction (toxicity impact category), calculations have been carried out for a spatial European model based on a 200×250 km grid. A multicontinental version of this model has been made available, for the assessment of emission inventories taking place in all the continents
EDIP 2003	Hauschild and Potting (2005)	v1.02	Midpoint	19	Europe (factors for up to 44 regions or countries within Europe as well as a European average value). Global for global impact categories
Eco-indicator 99	Goedkoop and Spriensma (2001)	Hierarchist, v2.07	Endpoint[b]	11	Global impact categories for climate, ozone depletion and resources. European model for other impact categories: all emissions are assumed to take place in Europe. Damage occurring outside Europe is also considered while using the European impact situation, if atmospheric lifetime is long (some toxic substances, some radioactive substances etc.). Acidification/eutrophication based on Dutch model, land use based on Swiss model
TRACI 2	Jane et al. (2002)	v3.03	Midpoint	9	Emissions in the USA, impacts throughout North America for acidification, eutrophication, and smog formation, and throughout the world for ozone depletion and global warming. Human and ecotoxicity are not site specific in TRACI, but U.S. EPA values for human exposure factors and risk assessment guidelines are used
ReCiPe Midpoint	Goedkoop et al. (2009)	Hieraschist, v1.04	Midpoint	18	Europe. Global for Climate change, ozone layer depletion and resources
ReCiPe Endpoint	Goedkoop et al. (2009)	Hieraschist, v1.04	Endpoint	17	Europe. Global for climate change, ozone layer depletion and resources.
Ecological Scarcity 2006	Frischknecht et al. (2009)	v1.05	Endpoint[c]	7	The original method has been developed for Switzerland. Various versions of the Ecological Scarcity method have been developed for other countries or part of the world

[a] Source: JRC (2010)

[b] Endpoint/midpoint method, but midpoint are not separated (JRC 2010)

[c] Distance to target approach. Endpoints indirectly considered by policy targets (JRC 2010)

important cause is the use of fertilizers in sugarcane culture. Results of applying different LCIA methods at midpoint level indicate that the decision about the best fuel will depend on which potential environmental impacts are prioritized. The selection of environmental impacts categories to be prioritized depends on which impacts are the most sensitive to the region and are also related to the society perception about these environmental impacts (which are reflected in the public policies).

Regarding the categories related to global warming (called "Global Warming" in CML, TRACI, EDIP 2003, and Impact 2002+ and "Climate Change" in ReCiPe Midpoint), expressed as kilograms of carbon dioxide equivalent (kg CO_2 eq). It is possible to notice that ethanol presents almost the same relative result compared to gasoline: 32.9 % in CML, 33.3 % in ReCiPe, 33.1 % in TRACI and EDIP, and 25.3 % in Impact 2002+. It reflects the fact that all the midpoint methods apply characterization factors based on

Table 2 Environmental impact categories for ethanol and gasoline using five different midpoint LCIA methods (functional unit, 1 MJ)

Method	Impact category	Unit	Ethanol	Gasoline	Lower impact[a]
CML 2 baseline 2000	Abiotic depletion	kg Sb eq	7.67E−05	4.43E−04	E
	Acidification	kg SO_2 eq	3.98E−04	1.90E−04	G
	Eutrophication	kg PO_4^{3-} eq	9.73E−05	3.42E−05	G
	Global warming (GWP100)	kg CO_2 eq	2.40E−02	7.29E−02	E
	Ozone layer depletion (ODP)	kg CFC−11 eq	1.59E−09	9.58E−09	E
	Human toxicity	kg 1.4−DB eq	6.59E−03	7.95E−03	E
	Fresh water aquatic ecotox.	kg 1.4−DB eq	2.10E−03	2.03E−03	G
	Marine aquatic ecotoxicity	kg 1.4−DB eq	2.83E+00	6.47E+00	E
	Terrestrial ecotoxicity	kg 1.4−DB eq	4.98E−05	5.57E−05	E
	Photochemical oxidation	kg C_2H_4	4.09E−05	1.75E−05	G
ReCiPe midpoint (H)	Climate change	kg CO_2 eq	2.42E−02	7.28E−02	E
	Ozone depletion	kg CFC−11 eq	1.58E−09	9.59E−09	E
	Human toxicity	kg 1.4−DB eq	1.73E−03	2.68E−03	E
	Photochemical oxidant formation	kg NMVOC	3.08E−04	1.52E−04	G
	Particulate matter formation	kg PM10 eq	3.42E−04	8.89E−05	G
	Ionizing radiation	kg U^{235} eq	9.37E−04	1.73E−03	E
	Terrestrial acidification	kg SO_2 eq	5.33E−04	1.99E−04	G
	Freshwater eutrophication	kg P eq	1.53E−06	2.19E−06	E
	Marine eutrophication	kg N eq	1.25E−04	4.45E−05	G
	Terrestrial ecotoxicity	kg 1.4−DB eq	5.79E−05	1.35E−05	G
	Freshwater ecotoxicity	kg 1.4−DB eq	5.31E−05	6.93E−05	E
	Marine ecotoxicity	kg 1.4−DB eq	3.80E−05	6.89E−05	E
	Agricultural land occupation	m^2a	6.05E−02	9.69E−03	G
	Urban land occupation	m^2a	9.69E−05	1.42E−04	E
	Natural land transformation	m^2	4.12E−06	2.66E−05	E
	Water depletion	m^3	6.76E−05	9.49E−05	E
	Metal depletion	kg Fe eq	7.30E−04	4.59E−04	G
	Fossil depletion	kg oil eq	3.93E−03	2.36E−02	E
TRACI 2	Global warming	kgCO_2 eq	2.42E−02	7.30E−02	E
	Acidification	H^+ moles eq	2.54E−02	1.06E−02	G
	Carcinogenics	kg benzen eq	2.23E−05	2.31E−05	E
	Noncarcinogenics	kg toluen eq	1.91E−01	2.12E−01	E
	Respiratory effects	kg PM2.5 eq	9.92E−05	4.30E−05	G
	Eutrophication	kg N eq	6.42E−05	4.78E−05	G
	Ozone depletion	kg CFC−11 eq	1.58E−09	9.58E−09	E
	Ecotoxicity	kg 2.4−D eq	1.05E−02	1.28E−02	E
	Smog	g NOx eq	2.70E−04	1.09E−04	G
EDIP 2003	Global warming 100[a]	kg CO_2 eq	2.42E−02	7.32E−02	E
	Ozone depletion	kg CFC11 eq	1.58E−09	9.58E−09	E
	Ozone formation (vegetation)	m^2.ppm.h	5.07E−01	2.58E−01	G
	Ozone formation (human)	person.ppm.h	3.51E−05	1.83E−05	G
	Acidification	m^2	5.97E−03	2.90E−03	G
	Terrestrial eutrophication	m^2	2.11E−02	4.93E−03	G
	Aquatic eutrophication EP(N)	kg N	6.30E−05	1.62E−05	G
	Aquatic eutrophication EP(P)	kg P	1.34E−06	1.91E−06	E
	Human toxicity air	m^3	7.31E+02	1.01E+03	E
	Human toxicity water	m^3	1.89E−01	1.74E−01	G
	Human toxicity soil	m^3	1.16E−02	7.50E−03	G

Table 2 (continued)

Method	Impact category	Unit	Ethanol	Gasoline	Lower impact[a]
	Ecotoxicity water chronic	m^3	1.57E+00	3.14E+00	E
	Ecotoxicity water acute	m^3	2.70E−01	5.06E−01	E
	Ecotoxicity soil chronic	m^3	2.21E−01	3.86E−02	G
	Hazardous waste	kg	1.80E−07	3.50E−07	E
	Slags/ashes	kg	4.48E−06	2.52E−06	G
	Bulk waste	kg	2.21E−03	7.80E−04	G
	Radioactive waste	kg	1.29E−07	2.46E−07	E
	Resources (all)	kg	1.38E−06	1.89E−06	E
IMPACT 2002+	Carcinogens	kg C_2H_3Cl eq	7.43E−05	3.07E−03	E
	Non−carcinogens	kg C_2H_3Cl eq	2.41E−04	1.74E−04	G
	Respiratory inorganics	kg PM2.5 eq	2.12E−04	5.18E−05	G
	Ionizing radiation	Bq C−14 eq	9.77E−02	1.81E−01	E
	Ozone layer depletion	kg CFC−11 eq	1.58E−09	9.58E−09	E
	Respiratory organics	kg C_2H_4 eq	5.36E−05	5.49E−05	E
	Aquatic ecotoxicity	kg TEG water	8.48E−01	2.32E+00	E
	Terrestrial ecotoxicity	kg TEG soil	5.17E−01	5.85E−01	E
	Terrestrial acid/nutri.	kg SO_2 eq	3.55E−03	9.85E−04	G
	Land occupation	m2org.arable	6.36E−02	1.02E−02	G
	Aquatic acidification	kg SO_2 eq	4.80E−04	1.99E−04	G
	Aquatic eutrophication	kg PO_4 P−lim	2.28E−06	5.65E−06	E
	Global warming	kg CO_2 eq	1.77E−02	6.99E−02	E
	Nonrenewable energy	MJ primary	1.76E−01	1.01E+00	E
	Mineral extraction	MJ surplus	1.98E−04	1.05E−04	G

[a] *E* ethanol form sugarcane, *G* gasoline

global warming potentials from the Intergovernmental Panel on Climate Change, the most scientifically robust consensus-based model available (JRC 2011).

Another environmental impact category that can be compared between different methods is the ozone layer depletion (called “Ozone Depletion” in ReCiPe, TRACI and EDIP, and “Ozone Layer Depletion” in CML and Impact 2002+), expressed as kilograms of chlorofluorocarbons equivalent (kg CFC-11 eq). A relative comparison shows that ethanol presents 16.5 % of gasoline’s impacts, whichever method has been chosen. For impacts like eutrophication and toxicity, which have different indicators to different ecological compartments depending on the method, this quantitative comparison is not possible. An example of the differences between methods for similar categories can be illustrated by acidification: even though ethanol always presents higher impacts than gasoline, the quantitative results are not similar using different LCIA methods. Gasoline acidification indicator represents 47.5 % of the one calculated to ethanol in CML (acidification, as kg SO_2eq), 37.3 % in ReCiPe (terrestrial acidification, as kg SO_2eq), 48.7 % in EDIP (acidification, as square meter), 41.6 % in TRACI (Acidification, as H^+ moles eq), and in Impact 2002+, 27.7 % looking at terrestrial acidification (as kg SO_2 eq) and 41.5 % when aquatic acidification (as kg SO_2 eq) is chosen. For acidification, the results are not convergent due the differences in characterization factors, which are spatially specific, and different characterization models adopted by each method.

It is important to notice that the environmental mechanisms at midpoint level were developed in other regions covering other context and environmental problems. In doing so, some environmental impact categories may not reflect the ethanol production from sugarcane in the Brazilian context. For example, acidification and photo-oxidant formation are modeled in the European context in the CML method; and in the TRACI, the impacts for acidification, eutrophication, and smog formation are modeled for North America, and for human and ecotoxicity; US EPA values for human exposure factors and risk assessment guidelines are used.

3.2 Comparison using endpoint indicators

An alternative strategy to midpoint characterization modeling takes as a starting point that the purpose of LCA is to reveal contributions to impacts on the areas of protection (human health, ecosystems, and resources) and, consequently, LCIA

must model the impacts on these. In this damage-oriented approach, characterization modeling must include the entire environmental mechanism. Consequently, this approach to characterization modeling is referred to as endpoint modeling allowing to aggregate the environmental impacts into a single-score indicator from normalization and weighting indicators from the different areas of protection. Normalization and weighting steps are often based on social science and/or economic metrics; being geographically specific. A potential benefit of the endpoint indicators is the increased possibilities of comparing impacts at an endpoint level, e.g., human health impacts from toxicological effects from those of climate change, if both can be modeled within the same framework (Finnveden et al. 2009).

The breakdown of single-score results for ethanol and gasoline life cycle environmental impacts of the four damage-oriented LCIA methods evaluated in this study is shown in Table 3. Ecological Scarcity is formally a distance to target approach. However, endpoint characterization is indirectly considered by policy targets (Frischknecht et al. 2009). Therefore, it is still a distance to target rather than a damage-oriented impact assessment method. In this study, Ecological Scarcity 2006 is evaluated in this section, among the endpoint characterization methods because it is also possible to aggregate its results into a single-score indicator.

Table 3 shows that environmental impacts of ethanol are worse than gasoline when LCIA methods assign great importance to categories related to particulate emissions to air, emissions to soil and water, and land use in the ethanol life cycle. Particulate emissions in ethanol life cycle are mainly associated to the bagasse combustion for heat and electricity generation in the industrial boiler since in this work we consider that sugarcane is harvested mechanically without preharvesting burning. It must be noted that these emissions are probably overestimated in our analysis as emission factors from small industrial boiler have been considered (GREET 2010). Another important point is that these emissions from bagasse burning in industrial boilers occur at field, in areas with low population density. Therefore, lower impacts could be expected if more accurate data for emission in modern industrial boilers used in the sugarcane industry in Brazil were available. Land occupation, which is intrinsic to agricultural cultivation of sugarcane, also contributes to the high single-score indicators for ethanol, as well as the emissions into water and soil which are mainly related to pesticides and fertilizers emissions on sugarcane culture. In the case of gasoline, the use of nonrenewable energy and global warming are the categories that mostly contribute for its single-score indicators. Application of different single-score LCIA methods in the comparison ethanol versus gasoline show that conclusions depend on the selected method.

Regarding the ethanol single-score results, the relative contribution of the categories respiratory inorganics in IMPACT2002+ and Eco-indicator 99 (H) methods and particulate matter formation in ReCiPe endpoint (H) method can be compared. Both categories are related to emissions of particulates, sulfur oxides, ammonia, and nitrogen oxides, with some little differences in characterization step, and all of them are expressed in Disability Adjusted Life Years (DALY), at endpoint level. While in IMPACT 2002+ method the category respiratory inorganics represents 70.6 % of single-score results for ethanol, in Eco-indicator 99 (H) it represents 44.0 %, as well as the category particulate matter formation in ReCiPe Endpoit (H) method, which represents 46.7 % of the single-score result. This fact reflects mainly the differences between the normalization and weighting factors (with some deviations due to differences in characterization step) and shows the great difference in the single-score results for similar impact categories.

Another comparison can be made between the relative weight of land use in Eco-indicator 99 (H) and IMPACT 2002+ methods. In the first LCIA method, the category land use represents nearly 44 % of the single-score result; while in the second one, the category land occupation accounts for only 17 % of the total result. The categories related to land use in ReCiPe Endpoint (H) method, agricultural and urban land occupations, have a small contribution to total single-score result and are grouped in “others” in Table 3. The Ecological Scarcity method present no specific environmental impact category related to land use.

Besides having different participation on single-score results in each method, the categories Energy Resources in Ecological Scarcity, Fossil Fuels in Eco-indicator 99 (H) and Non-renewable Energy in IMPACT 2002+ show similar results between ethanol and gasoline. Results for this impact for ethanol represents about 17 % of the results for gasoline (17.6 % in Ecological Scarcity, 16.0 % in Eco-indicator 99 (H), and 17.4 % in IMPACT 2002+). Although these results indicate a convergence of these three methods to the same relative results between ethanol and gasoline, the participation of these categories in the single-score results is quite different among the methods. It is due to different weighting factors adopted by each method for similar categories in the calculation of the single-score indicator.

Figure 1 shows the comparative results of single-score environmental impact indicators for ethanol and gasoline life cycle using four selected endpoints LCIA methods. Single-score results show that gasoline presents lower potential environmental impacts than ethanol when using IMPACT 2002+, Ecological Scarcity 2006, and Eco-indicator 99 (H) while ethanol presents better results than gasoline when using the ReCiPe Endpoint (H) LCIA method. Different LCIA methods use different normalization and weighting factors to compose the single-score indicator and these

Table 3 Characterization and single-score results for ethanol and gasoline using four different endpoint LCIA methods (functional unit, 1 MJ)

Method	Damage category	Impact category	Characterization unit	Characterization		Single score		Lower impact[a]
				Ethanol	Gasoline	Ethanol	Gasoline	
ReCiPe Endpoint (H)[a]	Human health	Climate change human health	DALY	3.39E−08	1.02E−07	7.54E−04	2.27E−03	E
		Ozone depletion	DALY	4.21E−12	2.53E−11	9.37E−08	5.63E−07	E
		Human toxicity	DALY	1.21E−09	1.88E−09	2.70E−05	4.17E−05	E
		Photochemical oxidant formation	DALY	1.20E−11	5.94E−12	2.67E−07	1.32E−07	G
		Particulate matter formation	DALY	8.89E−08	2.31E−08	1.98E−03	5.14E−04	G
		Ionizing radiation	DALY	1.54E−11	2.84E−11	3.42E−07	6.31E−07	E
	Ecosystems	Climate change ecosystems	species.yr	1.92E−10	5.77E−10	8.94E−05	2.69E−04	E
		Terrestrial acidification	species.yr	3.09E−12	1.15E−12	1.44E−06	5.38E−07	G
		Freshwater eutrophication	species.yr	6.70E−14	9.64E−14	3.12E−08	4.49E−08	E
		Terrestrial ecotoxicity	species.yr	7.35E−12	1.72E−12	3.42E−06	8.01E−07	G
		Freshwater ecotoxicity	species.yr	1.38E−14	1.80E−14	6.43E−09	8.39E−09	E
		Marine ecotoxicity	species.yr	3.04E−17	5.51E−17	1.42E−11	2.57E−11	E
		Agricultural land occupation	species.yr	1.11E−09	1.78E−10	5.17E−04	8.27E−05	G
		Urban land occupation	species.yr	1.87E−12	2.74E−12	8.70E−07	1.27E−06	E
		Natural land transformation	species.yr	7.62E−12	3.87E−11	3.55E−06	1.80E−05	E
	Resources	Metal depletion	$	5.22E-05	3.28E−05	7.08E−07	4.45E−07	G
		Fossil depletion	$	6.32E−02	3.79E−01	8.58E−04	5.14E−03	E
Eco-indicator 99[b]	Human health	Carcinogens	DALY	2.34E−09	1.64E−09	8.01E−05	5.62E−05	G
		Resp. organics	DALY	1.19E−10	1.20E−10	4.08E−06	4.11E−06	E
		Resp. inorganics	DALY	1.50E−07	3.68E−08	5.13E−03	1.26E−03	G
		Climate change	DALY	5.28E−09	1.54E−08	1.81E−04	5.26E−04	E
		Radiation	DALY	1.97E−11	3.64E−11	6.74E−07	1.25E−06	E
		Ozone layer	DALY	1.67E−12	1.01E−11	5.72E−08	3.44E−07	E
	Ecosystem quality	Ecotoxicity	PDF.m^2.yr	3.06E−03	3.37E−03	2.14E−05	2.36E−05	E
		Acidification/ eutrophication	PDF.m^2.yr	3.70E−03	1.03E−03	2.59E−04	7.17E−05	G
		Land use	PDF.m^2.yr	7.34E−02	1.23E−02	5.13E−03	8.57E−04	G
	Resources	Minerals	MJ surplus	4.00E−04	1.99E−04	1.59E−05	7.90E−06	G
		Fossil fuels	MJ surplus	2.12E−02	1.32E−01	8.42E−04	5.26E−03	E
Impact 2002+[c]	Human health	Carcinogens	DALY	2.08E−10	8.59E−09	2.93E−08	1.21E−06	E
		Noncarcinogens	DALY	6.75E−10	4.87E−10	9.52E−08	6.86E−08	G
		Respiratory inorganics	DALY	1.49E−07	3.62E−08	2.10E−05	5.11E−06	G
		Ionizing radiation	DALY	2.05E−11	3.81E−11	2.89E−09	5.37E−09	E
		Ozone layer depletion	DALY	1.66E−12	1.01E−11	2.34E−10	1.42E−09	E
		Respiratory organics	DALY	1.14E−10	1.17E−10	1.61E−08	1.65E−08	E
	Ecosystem quality	Aquatic ecotoxicity	PDF.m^2.yr	4.26E−05	1.17E−04	3.11E−09	8.51E−09	E
		Terrestrial ecotoxicity	PDF.m^2.yr	4.09E−03	4.63E−03	2.98E−07	3.38E−07	E
		Terrestrial acid/nutri	PDF.m^2.yr	3.70E−03	1.02E−03	2.70E−07	7.48E−08	G
		Land occupation	PDF.m^2.yr	6.93E−02	1.11E−02	5.06E−06	8.13E−07	G
	Climate change	Global warming	Kg CO_2 eq	1.77E−02	6.99E−02	1.78E−06	7.06E−06	E
	Resources	Nonrenewable energy	MJ primary	1.76E−01	1.01E+00	1.16E−06	6.66E−06	E
		Mineral extraction	MJ primary	1.98E−04	1.05E−04	1.31E−09	6.89E−10	G

Table 3 (continued)

Method	Damage category	Impact category	Characterization unit	Characterization		Single score		Lower impact[a]
				Ethanol	Gasoline	Ethanol	Gasoline	
Ecological scarcity 2006[d]	–	Emission into air	UBP	4.21E+01	3.67E+01	4.21E+01	3.67E+01	G
		Emission into surface water	UBP	2.10E+00	2.66E+00	2.10E+00	2.66E+00	E
		Emission into ground water	UBP	2.46E+00	3.93E−01	2.46E+00	3.93E−01	G
		Emission into top soil	UBP	1.38E+01	2.24E+00	1.38E+01	2.24E+00	G
		Energy resources	UBP	5.87E−01	3.34E+00	5.87E−01	3.34E+00	E
		Natural resources	UBP	6.26E+00	1.12E+00	6.26E+00	1.12E+00	G
		Deposited waste	UBP	3.45E−01	6.12E−01	3.45E−01	6.12E−01	E

DALY Disability Adjusted Life Years, *E* ethanol-form sugarcane, *G* gasoline

[a] Normalization values for the world (74.11 $DALY^{-1}$ for human health, 1,164 $species^{-1}$ $year^{-1}$ for ecosystems and 4.52 10^{-5} $\$^{-1}$ for resources) with the weighting set belonging to the hierarchist perspective (300 for human health, 400 for ecosystems, and 300 for resources; Goedkoop et al. 2009; PRé Consultants 2011)

[b] Normalization values for Europe (114.1 $DALY^{-1}$ for human health, 1.75 10^{-4} PDF^{-1} m^{-2} $year^{-1}$ for ecosystem quality and 1.33 10^{-4} $MJ_{surplus}{}^{-1}$ for resources) with the weighting set belonging to the hierarchist perspective (300 for human health, 400 for ecosystem quality, and 300 for resources; Goedkoop and Spriensma 2001; PRé Consultants 2011)

[c] Normalization factors for Europe (141 $DALY^{-1}$ for human health, 7.30 10^{-5} PDF^{-1} m^{-2} $year^{-1}$ for ecosystem quality, 1.01 10^{-4} $kg_{CO2eq}{}^{-1}$ for climate change, and 6.58 10^{-6} $MJ_{primary}{}^{-1}$ for resources) with the default weighting factor of one for all the scores (Jolliet et al. 2003; PRé Consultants 2011)

[d] Distance to target method developed for Switzerland. As all impact categories are expressed in the same unit UBP, the weighting step simply adds up the scores (Frischknecht et al. 2009; PRé Consultants 2011)

factors have great influence on the single-score results. The consistency between the endpoint methods is not the issue because the results are strongly affected by the normalization and weighting factors. Weighting is an optional step according to ISO and it might be needed when trade-off situations occur in LCAs used for comparisons (JRC 2010).

Results from using single-score indicators at endpoint level show that conclusions about which fuel present lower environmental impacts depends on which LCIA method is used in the evaluation. Different methods assign different normalization and weighting factors to different environmental impact categories and these considerations can change the results dramatically, limiting the interpretability of results. Biofuels have been recognized as a good alternative for mitigation of environmental impacts in comparison to fossil fuels (Macedo et al. 2008; Cherubini and Ulgiati 2010; González-García et al. 2010; Halleux et al. 2008; Macedo 2005; Ometto et al. 2009; Renouf et al. 2010, 2011; Seabra et al. 2010; Seabra 2008; Walter et al. 2011). However, results showed that only one out of four commonly used endpoint LCIA methods, the ReCiPe Endpoint (H), was able to quantitatively demonstrate the benefits of ethanol life cycle in relation to gasoline as an alternative transport fuel. As demonstrated in Table 3, the normalization and weighting factors used by each method have strong influence in these results. It is also important to notice that the environmental mechanisms and weighting factors used to compose the single-score indicators at endpoint level were developed in other regions with other societies' values and environmental problems. In doing so, single-score indicators may not reflect the social and environmental values in the Brazilian context. For example, land use, a category which has high impact on the single-score indicator for ethanol production using the Eco-indicator 99 LCIA method (see Table 3) might not be a major problem in the sugarcane growing region in Brazil. According to Finnveden et al. (2009), the principal discrepancy between midpoint and endpoint modeling lies in the evaluation of whether the uncertainty in midpoint versus endpoint modeling is

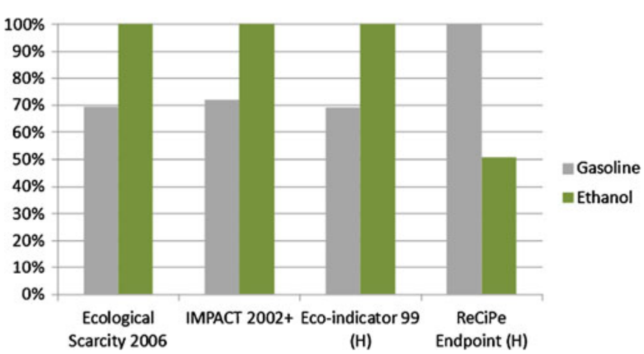

Fig. 1 Comparative single-score results for ethanol and gasoline life cycle environmental impacts using four different endpoints LCIA methods

justified by the improved interpretation of the results, and the answer varies between the different categories of impact and different practitioners/clients. While reliable endpoint modeling seems within reach for some of the impact categories like acidification, cancer effects, and photochemical ozone formation, it is still developing for climate change, where a midpoint approach will choose the indicator rather early in the environmental mechanism (at the level of radioactive forcing), and where endpoint modeling is encumbered with large uncertainties due to the many unknowns of the global climate system and to the long time horizon of some of the involved balances.

The great difference in single-score results using different endpoint LCIA methods occurs, besides normalization and weighting factors, due to immaturity in characterization models, that does not allow to recommend a specific LCIA method (JRC 2011). Even thought all endpoint methods evaluated are considered immature, ReCiPe was pointed by the Joint Research Commission of European Union as the best interim method to European context (JRC 2011). Nevertheless, it is not possible to affirm that this is the best endpoint method to evaluate sugarcane impacts in the Brazilian context. There are some examples in literature of best approaches for LCIA but they have not resulted in a uniform, globally accepted set of LCIA methods (Udo de Haes et al. 2002; Finnveden et al. 2009). Therefore, further research is necessary in order to establish a guide on how to choose a LCIA method for life cycle assessment of bioenergy systems. The decision about the value of reporting single-score results will depend on the specific scope and objectives of the study. The work towards establishing consistent methods for end-point indicators requires a much broader discussion (Finnveden et al. 2009).

4 Conclusions

The results presented in this study show that the use of different LCIA methods can lead to different comparative environmental impacts of ethanol and gasoline, mainly when single-score indicators are applied. There is a relative convergence in the results of equivalent environmental impact categories using different midpoint LCIA methods. Results of the comparison of the five midpoint LCIA methods showed that ethanol presents better environmental performance than gasoline in important categories such as global warming, fossil depletion, ecotoxicities, and ozone layer depletion and worse environmental performance than gasoline in the categories acidification, eutrophication, photochemical oxidation, and agricultural land use. Results of applying different LCIA methods at midpoint level indicate that the decision about the best fuel will depend on which environmental impacts are prioritized. The selection of environmental impacts categories to be prioritized depends on which impacts are the most sensitive to the region and are also related to the society perception about these environmental impacts (which are reflected in the public policies).

It was not possible to establish which LCIA endpoint method is more appropriated to the comparative evaluation of environmental impacts of ethanol and gasoline. ReCiPe Endpoint was the only single-score LCIA method that was able to show that ethanol presents better results than gasoline in a broader spectrum of environmental impacts. Using IMPACT 2002+, Eco-indicator 99, and Ecological Scarcity 2006, higher scores are verified for ethanol, mainly due to the categories related to particulate emissions and land use. However, the environmental mechanisms and weighting factors used for compose indicators at midpoint or endpoint level was developed in other regions with other societies' values, context, and environmental problems. In doing so, these indicators may not reflect the specific social and environmental attributes in the Brazilian context.

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